TR-1075

SOME ENGINEERING CONSIDERATIONS OF THE HUMAN CARDIOVASCULAR SYSTEM
(The Resonant Arterial System)

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ORDNANCE CORPS ● DEPARTMENT OF THE ARMY

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Glossary of Medical Terms*

Atrial	- Of or relating to an atrium (auricle)
Auricle	- The chamber or one of the two chambers of the heart by which the blood is received from the veins and forced into the ventricle or ventricles.
Cardiovascular	- Of, relating to, or involving the heart and blood vessels.
Diastole	- The passive rhythmical expansion or dilatation of the cavities of the heart during which they fill with blood.
Myocardial	- Of, relating to, or involving the myocardium, the middle muscle layer of the heart wall.
Perfuse	- To cause to flow
Pulmonary Circulation	- The passage of venous blood from the right auricle of the heart through the right ventricle and pulmonary arteries to the lungs where it is oxygenated and its return via the pulmonary veins to enter the left auricle and participate in the systemic circulation.
Renal	- Of, relating to, or involving the kidneys
Systemic Circulation	- The passage of arterial blood from the left auricle of the heart through the left ventricle, the systemic arteries, and the capillaries to the organs and tissues that receive much of its oxygen in exchange for carbon dioxide and its return via the systemic veins to enter the right auricle and participate in the pulmonary circulation.
Systole	- The contraction of the heart by which the blood is forced onward and the circulation kept up.
Trauma	- An injury or wound to a living body caused by the application of external force or violence.
Vascular	- Of, relating to, or affecting a tube for the conveyance of a body fluid.
Ventricle	- A chamber or one of the chambers of the heart which receives blood from a corresponding atrium and from which blood is forced into the arteries.

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*Definitions from Webster's Third New International Dictionary, 1961.

ABSTRACT

A study was made from an engineering viewpoint primarily to determine the need for (1) a human heart that produces a pulsating rather than steady flow and (2) an elastic circulatory system. It is suggested that the normal rhythmic contractions of the heart may produce pulsed flows which resonate with the natural frequencies of the arterial system. As a consequence the magnitudes of the myocardial forces and energies expended by the heart would then be minimal and tightly bounded for large flow rate variations. Sufficiently great and uncorrected changes in either or both the resonant character of the arterial system or the pulsed flows may cause the heart to overwork and die prematurely or may result in other system malfunctions. Resonance then may possibly be a major physical design principle upon which the human cardiovascular system is based and which allows it to operate within its many constraints.

1. THE PROBLEM

During work on the design of a blood pump for extracorporeal applications, it became apparent that in spite of the existing large body of medical knowledge describing the cardiovascular system and its functions, several rather basic questions pertaining to its design still lacked answers. Perhaps the most basic question to be answered is the one: "Is it necessary to have a heart that produces pulsating rather than steady flows and an elastic circulatory system?"

As the pump design progressed, a number of interesting similarities were revealed between the resonant characteristics of familiar mechanical and electrical systems and the dynamic character of the pulsed blood flows from the heart and responses of the arterial system. This led to the study described herein in which an answer to the above question is sought.

The following factors are considered particularly pertinent:

(1) Man's active environment and the compactness of his body, achieved in part by the multiple tasks performed by the blood, suggest the need for a closed, forced circulation, cardiovascular system.

(2) To perform the multifunctional role, the blood is required to be a highly complex fluid of which certain elements are easily damaged by trauma.

(3) The susceptibility of the blood to trauma requires a heart that squeezes with minimal force. Forces may be minimized both by causing variable resistive loads to play an important role in regulating the flows from a relatively constant pressure pump (the heart) and by employing resonant principles.

(4) Because of fatigue limits of cardiovascular materials, inefficiencies of heart and circulatory system, limited squeezing capabilities of myocardial muscles, and the finite energies available, the heart and circulatory system are designed to keep these limiting criteria within bounds. These bounds are fired so that irreversible damage is not done to elements of the system or blood, under defined functional conditions.

(5) These bounds are commensurate with the capabilities of the body to repair or replace materials damaged during normal functioning of the body.

(6) It is possible that only a rhythmically beating heart forcing blood into and through an elastic arterial system in which the natural or commanded responses are uniquely related to the pulsed blood flows could achieve forces and expend energies sufficiently great to realize the required vascular pressures and flows. Simultaneously these forces and the resulting pressure and flows must be compatible with the heart's limited ability to generate them, the vessel's ability to contain them, and the blood's ability to tolerate them.

A mechanical system having requirements similar to those of the arterial system and the design principles used to satisfy these are discussed. It is suggested that these same principles may apply to the arterial system.

2. EXPLANATIONS FOR AN ELASTIC CIRCULATORY SYSTEM

One of the most readily observed characteristics of the vascular system is that the vessels are highly distensible, and increases in flow cause them to distend reducing resistance to flow. Consequently only small increases in blood pressure are needed to obtain large increases in flow. This, of course, means that the heart does not have to work as hard (for adequate perfusion) as it would for systems in which the resistance did not decrease.

Gregg (ref 1, p 278) offers another reason for an elastic circulatory system, which seems to be generally in accord with the opinions of others in the medical field. He states that the elasticity of the vessel walls "is concerned mainly with the origin and maintenance of the diastolic blood pressure and with sustaining the mean pressure at a higher level than would be possible in a rigid system under otherwise identical conditions" because the kinetic energy of the systole is in part stored as potential energy in the distended vessel walls. During diastole the potential energy is given up to the stream to drive the blood onward and to maintain diastolic pressures. Resistance to flow also shares in the maintenance of these pressures. If, however, the arterial system responds according to laws that govern damped resonant systems generally, as seems likely, then the elastic properties of the vessels have a broader role (point 6, sec 1) to play than only the maintenance of diastolic pressures and the lessening of flow resistance. Any

disturbance of these elastic properties can, if sufficiently great, cause the heart to work harder, shortening the life of the individual if uncorrected, or causing failure of vessel walls by overstressing.

These explanations do not justify a heart that produces a pulsatile flow contrasted to one that produces a nonpulsatile flow presuming this to be possible. They only justify an elastic circulatory system because a beating heart of limited capability exists. It might be suggested that the heart beats because locomotion of any magnitude within the body is always provided by muscles. Muscles can only pull, hence a beating heart employs the same muscular elements as elsewhere in the body. While this may be true it is felt that this is not the total reason for a rhythmically beating heart.

The following paragraphs suggest, partly from the viewpoint of the engineer, the considerations important in the construction of the human cardiovascular system.

3. THE MULTIFUNCTIONAL ROLE OF THE BLOOD

Compactness is a particularly desirable attribute in a system design. Whether in an engineering device or a living organism compactness is achieved, in part, by causing functional elements to perform more than a single task. The human body illustrates the degree to which this can be carried, and its achievement is made possible by the multifunctional character of the blood flowing in a closed circulatory system.

Best (ref 1, p 2) describes the major functions of the blood in supplying body needs as follows. The processes of respiration, nutrition and excretion are made possible by the simultaneous conveyance within the blood of materials peculiar to each process to the appropriate regions of the body for assimilation, expulsion, etc. The blood assists in maintaining the water content of the tissues by transuding fluids through the vessel walls. This allows the processes of respiration, nutrition and excretion to operate. Because of the blood's high specific heat, thermal conductivity, and latent heat of evaporation, it helps to regulate body temperature to the precise degree required for life. Further its mobile character allows it to be quickly redistributed to regions of the body requiring immediate temperature adjustment. Protective and other regulatory functions in the body's defense against injurious agents of various kinds are also performed by the blood.

(In contrast an internal combustion automobile engine with needs similar to that of the body - fuel, oxygen, waste removal, temperature regulation, etc - requires many separate, distinct systems to perform an equivalent number of tasks.)

Man's compactness and his active environment indicate the need for a forced-circulation cardiovascular system. Capillary and osmotic systems, for example, while occupying small spaces, are not practicable because of their limited ability to convey sufficient amounts of the

necessary biological materials quickly enough to support the body processes. (In engineering systems compactness and the magnitude of the energies involved usually determine the need for forced circulation.)

4. BLOOD'S SUSCEPTIBILITY TO TRAUMA

It might be reasoned then that because the blood is required to perform so many tasks it is a highly complex fluid. It is also highly susceptible to physical trauma or shock. (There are, of course, other causes which create blood damage besides shock.) Shocks of relatively low magnitude cause the hemoglobin to escape from the red blood cells into the surrounding fluid. This process is called hemolysis or laking. If the rate of hemolysis is sufficiently great, free hemoglobin is excreted as such by the kidney. This may result in severe renal damage and death.

This fragile character of the blood places stringent requirements on the organ propelling it through the human circulatory system, which in itself causes observable damage because of its tortuous passageways.

In the design of pumps for extracorporeal applications it is found in general that the damaging action of the pump on the blood is usually great enough to limit pump runs during surgical repair of the heart to 1 to 2 hr. Most extracorporeal pumps are considerably different in design from that of the heart, which together with their high hemolysis rates suggests that the principles employed by the heart to control hemolysis are not known or at most not fully understood.

Therefore it is suggested that an important criteria determining the design of the heart is related to its ability to pump blood gently which, as suggested in this report, is achieved in part both by the heart's exploitation of the elastic properties of vessels and the methods used to control flows in the cardiovascular system. The fact that the normal heart produces hemolysis within tolerable limits for long-term perfusion and is able to achieve the necessary blood pressures and flows to satisfy body needs is obvious.

5. A PHYSICAL DESCRIPTION OF THE HEART

The heart is divided into two pumping sections - the right and the left. The right pumps blood from the terminus of the systemic circulation to the beginning of the pulmonary circulation, where the blood in passing through the lungs is oxygenated. The left takes oxygenated blood from the terminus of the pulmonary circulation and forces it into and through the systemic circulation, where the previously described processes occur.

These pumping sections have physical similarities. Each consists of a ventricle, an auricle and two valves. The auricles serve as plenum chambers to assure an adequate supply of blood to the ventricles. Blood upon dilation of the ventricles (the diastole) is forced from the auricles through the appropriate inlet valves into ventricles by residual auricular

pressures (slightly positive) and muscular action. Ventricular filling is accomplished chiefly by the difference between atrial and ventricular pressures during the period the difference is maximal. However atrial contraction plays a small but significant role in the filling process (ref 1, p 244). Upon contraction (the systole) blood is forced out through the outlet valves into and through the associated circulations.

The outlet valves (aortic-left heart, pulmonary-right heart) are tricuspid, semilunar valves. The inlet valve (tricuspid) for the right heart is also a tricuspid valve, while for the left heart it is a bicuspid valve (mitral). Both the tricuspid and mitral valves are prevented from inverting under the resulting ventricular peak pressures by chordae tendineae attached to the papillary muscles. These muscles during systole contract thereby aiding in the proper closure of the atrioventricular leaflets (ref 3, p 511).

The left ventricle resembles a cylinder with a conoid apical segment, while the right ventricle would appear to envelope a portion of the left ventricle and is spherical in shape. The common wall is called the septum.

During systole the energy expended in propelling the blood represents the combined efforts of various bundles of myocardial fibers. They are the superficial bulbo and sino spirals and the deep bulbo and sino spirals (ref 1, p 239). The superficial spiral muscles are attached at the top of the heart to the fibrous skeleton of dense connective tissue containing the four valve rings. These muscles flow diagonally around the surface of both ventricles converging at the apex. At the apex they are strongly twisted and make up the full wall thickness. These muscles form the inner thin layer of spiral muscle and the lower third of the septum by virtue of their penetration to the interior of both ventricles. Because the inner and outer spiral muscles cross each other obliquely at about 90 deg, their contraction causes the ventricle cavities to shorten longitudinally rather than rotationally.

Between the thin exterior and interior spiral muscles are interposed the heavy constrictor muscles. These make up the basilar two-thirds of the septum and lateral wall of the left ventricle. These deep circular fibers form a thin middle layer in the right ventricle, which contributes little to wall thickness compared with the spiral layers.

The left ventricle wall contains a large mass of circularly arranged constrictor fibers, which in contracting reduce the ventricular diameter with minimal shortening from apex to base. In contrast, the right ventricle with its dominance of spiral muscle causes both a longitudinal shortening of the chamber and transverse motion in which the right ventricle wall moves toward the convex surface of the septum. These contractile modes together with the heart and cardiovascular system's unique design may provide clues to the manner in which trauma to the blood is maintained at minimal levels.

6. AN ENGINEERING ANALOGY OF THE CV SYSTEM

Figure 1 shows an engineering analogy of the cardiovascular system. Depicted are the resistive and capacitive loads operative in the system and the pressure-sensing elements that participate in system control. The analogy does not include the chemoreceptors, which function to maintain desired chemical balances in the blood and the volume receptors.

The spring-lever-piston arrangement in the lower portion of the diagram represents an attempt to portray the various functional elements of the heart described earlier. Forces M_L and M_R are contractile forces the magnitude of which are governed by the endocrine system or the sympathetic nervous system. While these forces operate simultaneously, their relative magnitudes do not necessarily remain constant. The lever arrangement intends to demonstrate the degree of independence enjoyed by each ventricle. The contractile forces are augmented by the stretch mechanism which, in turn, is directly influenced by the residual atrial pressures.

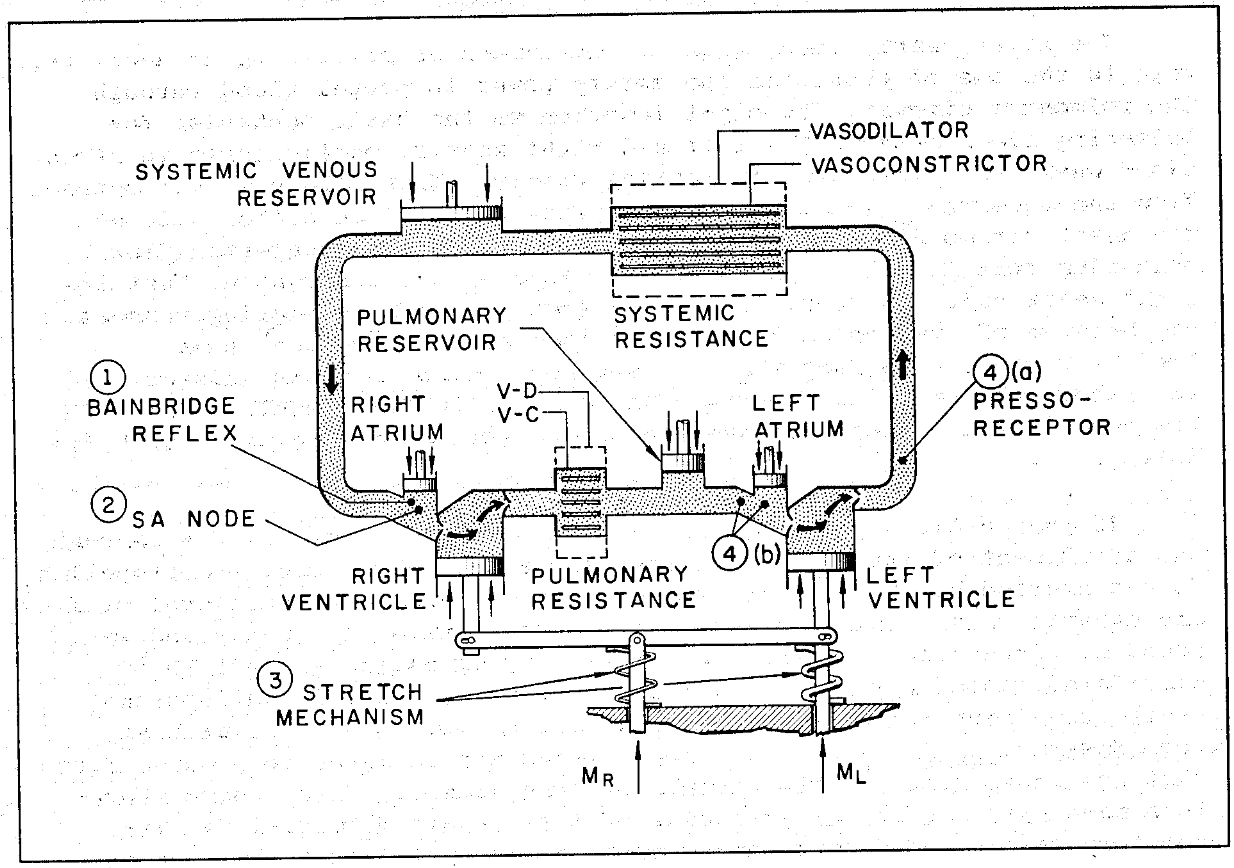
Both the resistive and capacitive loads are regulated through the processes of vasoconstriction or vasodilatation. Vasoconstriction is active in nature while vasodilatation is passive.

The functions of the various sensory elements are detailed below the diagram.

Perhaps the most important message presented by the diagram pertains to the roles played by each side of the heart. It suggests that the left heart is concerned primarily with maintaining a general level of flow in the system. This conclusion is based on the locations and functions of pressoreceptors 4a and 4b. Pressure fluctuations in the flow tracts before and after the left heart caused by variational flows are compensated by changes in systemic resistance and by pulse rate adjustment in the case of the outflow tract. The left heart does not possess a sensing element in the inflow tract, to increase its pulse rate in the presence of increased flows, as does the right heart.

The left heart, therefore, might be described as the prime mover of the cardiovascular system whose outputs are governed by the activity levels enjoyed by the individual. The diagram and logic would suggest the system pressures are maintained by alterations in systemic resistance, since for relatively constant activity levels smaller forces operate. This has the added advantage that pulse rate can become less variable.

On the other hand, the right heart would appear to play a somewhat subservient role to the left heart. The only sensing element affecting its flow apart from the control received through the SA node is the Bainbridge reflex. (Gregg suggests that this reflex is not well established as yet.) Increased flows to the right heart, as indicated by increased filling pressures, cause both sides to speed up simultaneously, but the right heart is not favored with load regulators. Consequently the right heart must adjust its pulse rate either through the operation of the



① BAINBRIDGE REFLEX:

PRESSORECEPTOR SENSES INCREASED FILLING PRESSURES. PULSE RATE CAUSED TO INCREASE, "UP" ONLY

② SA NODE:

RECEIVES SIGNAL FROM BRAIN, INITIATES DE-POLARIZING ACTION OF AV NODE. SIGNALS CONTROL PULSE RATE "UP" AND "DOWN".

③ STRETCH MECHANISM:

INCREASED FILLING PRESSURES CAUSE INCREASED CONTRACTILE FORCES AND VICE VERSA

④ PRESSORECEPTOR:

4a- SENSES ARTERIAL PRESSURES
Heart rate and systemic resistance are regulated to maintain constant arterial pressures

4b- INCREASED FILLING PRESSURES
Systemic resistance is caused to increase and vice versa

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Figure 1. Diagram of the human cardiovascular system.

Bainbridge reflex or the SA node to pass the flows it receives without change but with the addition of enough energy to meet pulmonary loads.

The right heart, then, might be described as performing an additional role to the one of providing the motive power to propel blood through the pulmonary circuit. It might function as the basic mechanism for balancing flows between the left and right hearts, particularly in situations where the flows are fluctuating widely. This role does not detract from the observed characteristic that flow output from either side of the heart varies directly with filling pressure. The suggested flow balancing role for the right heart is based on the observation that the right heart enjoys a peculiar freedom from pressure regulating sensors, and because of its design it is recognized as good "volume" pump (ref 2, p 444). The fact that it is a good volume pump is related to its spherical design and contractile mode. Relatively small changes in its radius produce large changes in stroke volume when compared with the left heart.

If the cardiovascular system exercises flow control chiefly through the adjustment of its peripheral resistance and pulse rate, the propelling forces exerted by the heart on the blood are minimal for any level of flow and dynamic relationship between the heart's beating frequency and responding circulatory system. No excess pumping energy is left to be dissipated wastefully and to increase hemolysis. This is an important design consideration both in the human system and in artificial heart pump designs. A few artificial heart pumps are designed to produce flows that are independent of the circulatory resistance. These pumps therefore have systolic energy in excess of that required to satisfy circulatory loading, and this energy must be dissipated as turbulence and other unnecessary losses.

Later paragraphs discuss the dynamic situation mentioned above, which establishes the relationship between myocardial forces and pressures.

7. CARDIOVASCULAR DESIGN LIMITATIONS

Many other (engineering) factors must also be considered to achieve a satisfactory cardiovascular system design, and all must be compatible with the heart's physical design and dynamic performance. For example, the repetitive stresses incurred by the muscle fibers of the heart and the vessels of the vascular system must be low enough to be commensurate with the body's ability to handle damaged tissue materials. If the stresses exceed some definable limit, the tissue materials will fail faster than the body can accomplish repair. A comparable limit in engineering materials such as steel, aluminum, etc, is known as the endurance limit and may be considerably lower than the ultimate or breaking strengths of the materials. As the magnitude of the repeated stresses is progressively reduced, the life of the material grows until a stress—the endurance limit—is reached below which the material can presumably live indefinitely without failure.

In the vascular system, excess pressures and/or weak vessel walls can produce aneurysms — a ballooning of the wall. Consequently blood pressures must be controlled below the limit causing these. Similarly the forces and energies required to achieve adequate blood pressures and flows must be commensurate with the heart's ability to produce them. They obviously cannot exceed these limits.

These factors — pressures, flows, stresses, energies and forces— are individually related to a host of other variables each of which must be compatible with total system design. These factors establish the bounds to system design and cause myocardial forces in particular to become tightly bounded.

8. RESONANCE — A POSSIBLE BASIC DESIGN DETERMINANT

A clue to the method employed by the human arterial system to satisfy such system requirements may exist in the principles governing the design of the familiar spring-actuated pendulum clock. The clock is able to operate because a sufficiently large force stored as potential energy in a wound spring is caused to act at precisely the right moment on the swinging pendulum. The pendulum is then forced to swing a necessary distance before a subsequent impulse can act on the pendulum. Yet the clock can operate for days or even weeks on relatively small energy investments because minute amounts of energy and correspondingly small forces are operating for each swing of the pendulum. The clock operates then because the force is caused to act in tune with the natural frequency of the pendulum. Any tampering with the natural frequency of the pendulum or the periodicity of the force can, if great enough, stop the clock. It is suggested that the human arterial system may employ these same resonant principles on a system basis to achieve its functional character. The fact that fluid resonances operate on a local basis is a fairly well established fact (ref 1, p 284).

To consider resonant phenomena in a general fashion, figure 2 is introduced. It shows a mass supported by a spring. The vibrations of the mass caused by the sinusoidal periodic motions of the base are viscously damped. The resulting vibrations of the mass are known to depend on the character of the mass, the spring, the damping force, and the cpm character of the exciting vibrations.

Now if one required the mass to vibrate at a fixed excursion by increasing or decreasing the force applied to the supporting base, it should be evident that its magnitude would depend on the natural resonance of the system and the frequency of the exciting forces.

Figure 3 shows the magnitude of this force as related to these frequencies. The natural frequency of the system was chosen as 210 for reasons stated below. For convenience in calculating the curves, the spring of figure 3 was assumed to have a deflection constant of 1 lb/ft. The

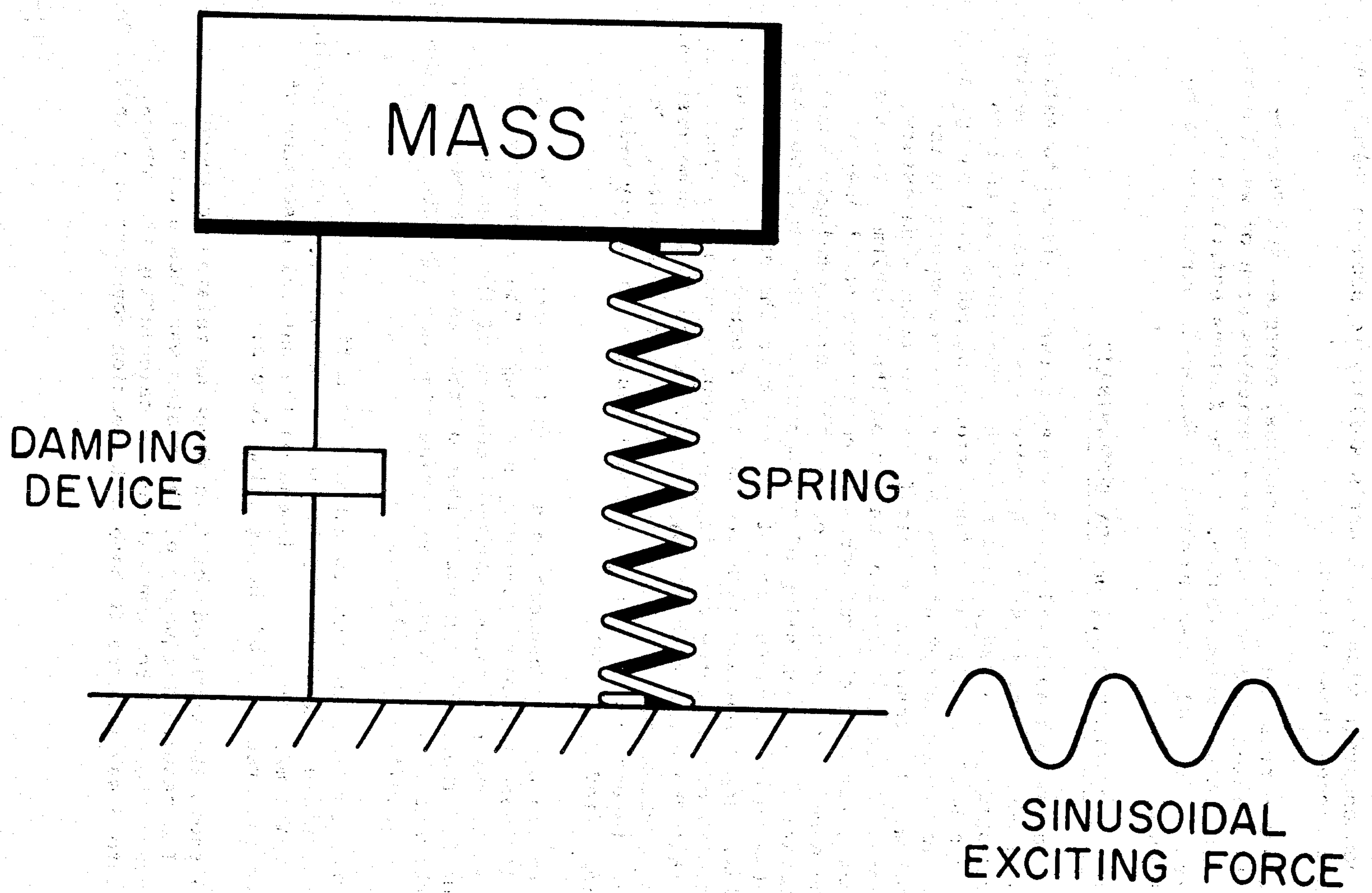

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Figure 2. Damped mass—spring system.

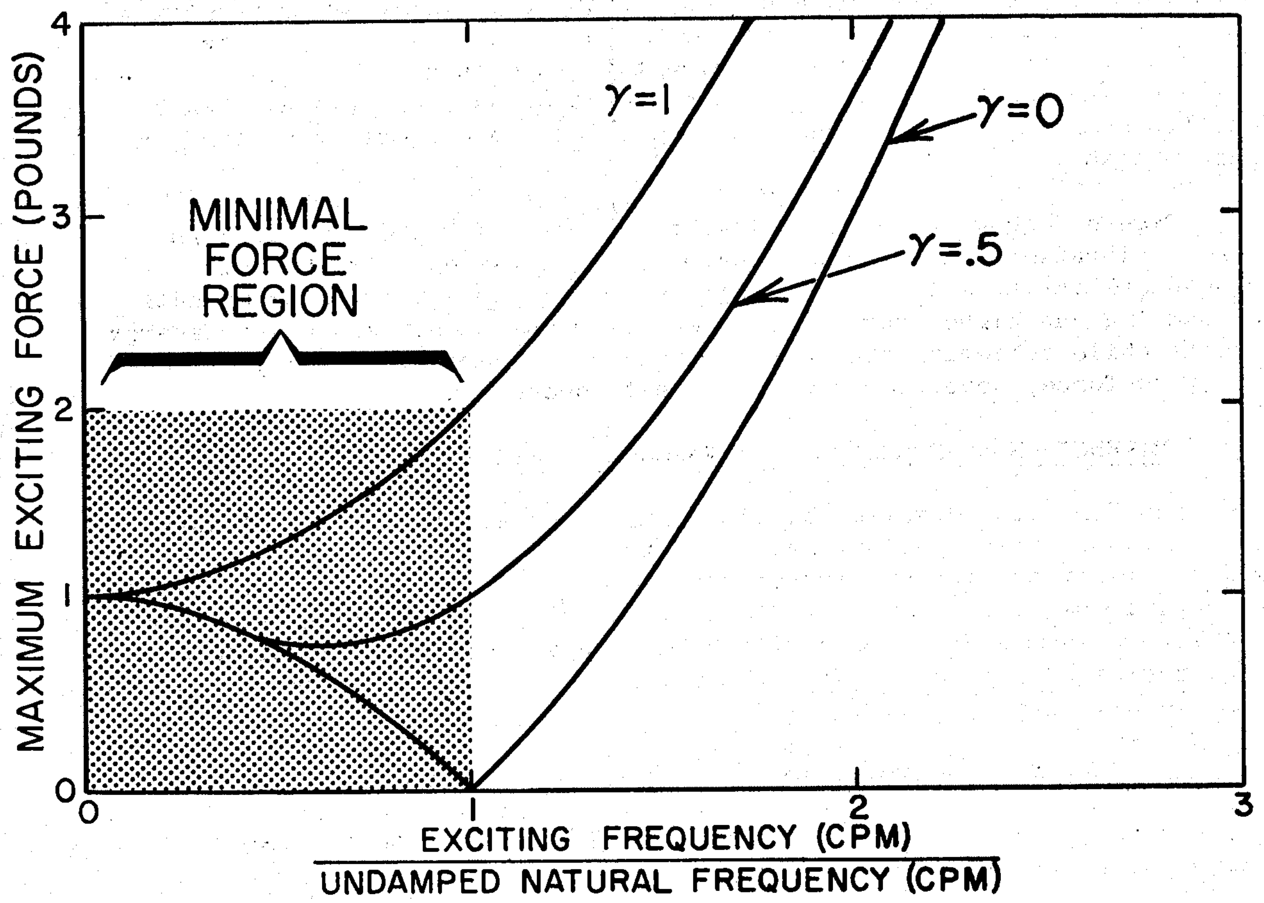

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Figure 3. Force characteristics in a resonant system (for a constant mass excursion).

base displacement was chosen as 1 ft. The effect of increased damping is depicted by the curves designated γ. For $\gamma = 0$, no damping exists, whereas for $\gamma = 1$, critical damping (no rebound) occurs. A natural frequency of 210 cpm was chosen because the arterial system in the human has a natural frequency of about 180 to 240 cpm (based on a conversation with Gregg). The heart is also a relatively constant-stroke variable-frequency pump (except for strenuous exercise situations). These assumptions might demonstrate similarities between resonant phenomena and the cardiovascular system.

Figure 3 suggests that a smaller pulsed force is necessary to deflect the mass a fixed distance if the pulse frequency is equal to or less than the natural frequency of the system, depending on the amount of damping present. Larger and larger amounts of force are necessary if the pulse frequency is caused to operate above the system's natural frequency. Hence in the region below the system's natural frequency, the exciting force, depending on the amount of damping present, can be made to decrease, remain constant or increase more slowly than for frequencies above resonance.

Figure 4 shows the energy lost to friction for the same 210-cpm system vibrating with an amplitude of 1 ft in response to the same sinusoidal variable-frequency exciting force. Both increasing amounts of damping and higher forcing frequencies cause higher and higher energy losses while achieving the desired fixed displacement. Energy, in contrast to force, never decreases as the frequency increases.

9. EVIDENCE OF A RESONANT CARDIOVASCULAR SYSTEM

Now since the arterial system consists of an elastic circulatory system pulsed by a beating heart, it might be interesting to examine similar relationships as plotted for the mass-spring system. It should be kept in mind that one is a fluid system while the other is a mechanical system. These relationships will be developed using the normal pulsing frequencies of the heart and the responses of the arterial system located immediately after the heart.

It is known that the pulse rate for a normal young adult varies from about 60 cpm (resting) to 160 to 180 cpm (heavy exercise) with rates for short exhaustive work to 240 to 270 cpm (ref 1, p 307). About the same limits hold for older persons.

If one forms frequency ratios (similar to those of fig. 3 and 4) of pulse rate to arterial resonance (using 210 cpm as a mean) out of these limiting values, the result is interesting. The ratio of low pulse limit to arterial resonance is about 0.3 and similarly for high pulse limit (heavy exercise) is about 0.8. These limits lie within the regions where resonant systems require minimum forces to maintain a desired fixed excursion (see fig. 3 and 4). A ratio of about 1.2 is achieved for exhaustive work, and it is in this region where resonant systems require

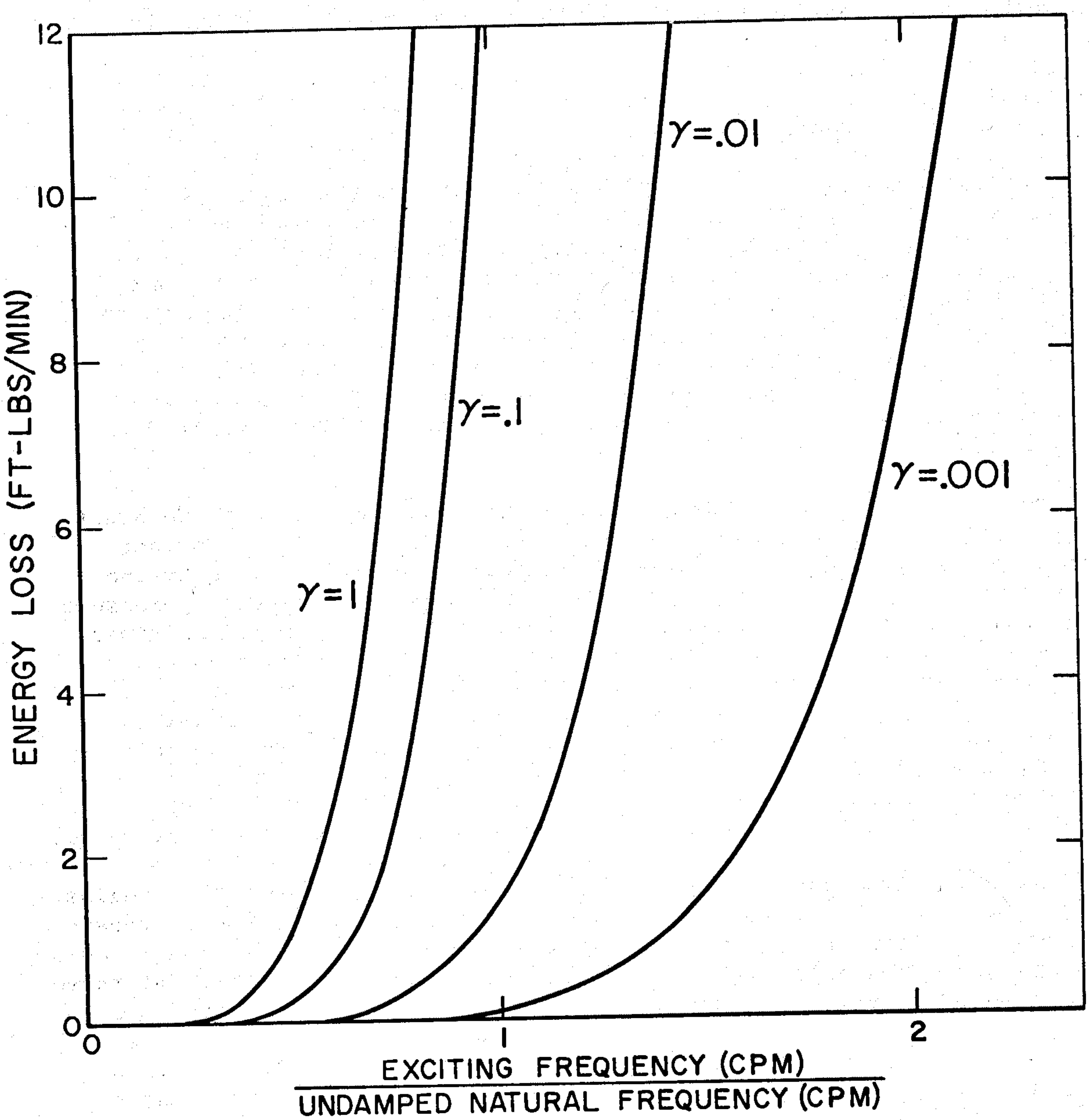

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Figure 4. Energy loss in a resonant system (for a constant mass excursion)

rapidly increasing amounts of force and energy. These ratios assume that the arterial resonance remains a constant. In reality it probably increases as the vessels distend under high rates of flow. Consequently the higher ratios would probably be lower than 1.2.

If the arterial system operates on damped resonant principles, it operates in precisely the frequency domain one would expect from a force-energy viewpoint. Above this region the heart would be expected to overwork rapidly, which it does. For frequency ratios less than the lower limit, inadequate perfusion is the consequence. If resonant principles hold, the potential energy stored in the vessel walls during systole is given up to the main stream in phase with the pulsed flows within the main stream.

Force (or stress) relationships similar to those in figure 3, but for the arterial system, can be shown in an approximate fashion. However before this can be shown it is necessary to introduce one other curve. Figure 5 shows an example of the variation of flow rate with maximum systolic pressure for the left heart (ref 1, p 306). (A maximum systolic pressure of 120 mm Hq for resting conditions was used in transposing the pressures from means to maximums.) Vasodilatation of the circulatory vessels resulting both from the elastic properties of the vessel walls and neuromuscular phenomena make large increases in flow possible for small increases in pressure.

To obtain the approximate myocardial squeezing force that the heart muscle must exert to achieve these pressures, the equation of LaPlace (ref 4, p 370) can be used. It must be modified by multiplying by the width of the muscle. The equation says that wall tension equals pressure times radius times muscle width. By letting the ventricle radius times muscle width equal K, which is assumed to be an independent constant, maximum myocardial force can be plotted as a function of frequency (fig. 6 - the solid line), and the shape of the curve can be examined without evaluating K. The curve suggests that for a 270-percent increase in flow rate between the pulse limits of resting to heavy exercise, muscle force increases only about 38 percent. Reference 1 (p 311) indicates an 800-percent rise in flow is possible for exhausting exercise.

Above the frequency ratio 0.8, the curve (dashed) most likely begins to rise more rapidly as shown in figure 6 (based on a telephone conversation with R. Olsen of Gregg's office). This presumes that the heart could meet the load demands placed on it, which in reality it can not. At these high rates of exertion, the pressure actually begins to drop since the heart starts to fail. The theoretical rise of muscle force in figure 6 is associated with the limited distensibility of the vessels. As this limit is reached, the natural arterial resonance ceases to rise, hence higher flows require higher pressures and more strokes per minute. (NOTE: Under extreme rates of exertion, the stroke volume apparently increases up to two to three times to achieve flows of 35 to 45 liters per minute - ref 1, p 311.)

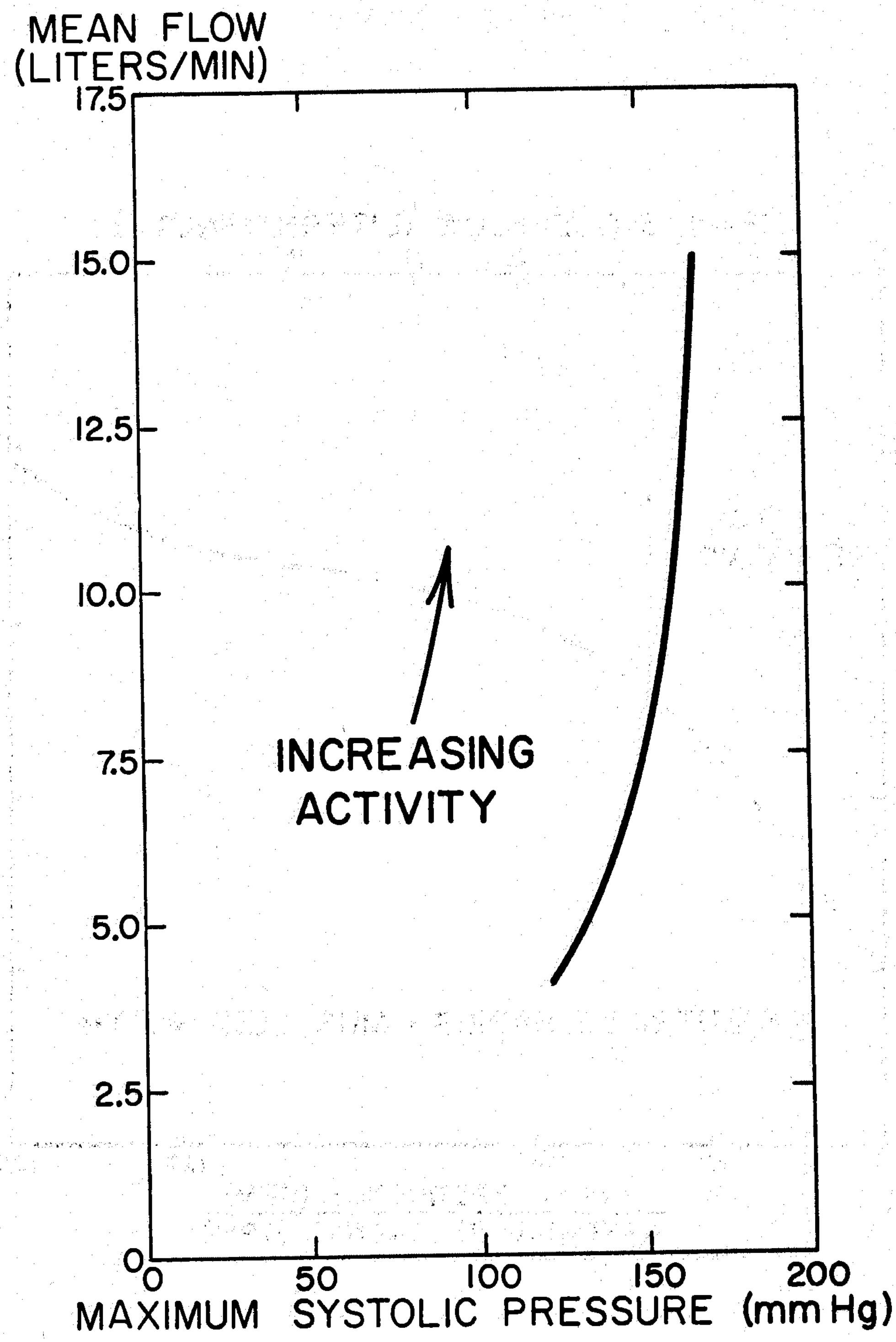

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Figure 5. Blood pressure versus flow (young adult males).

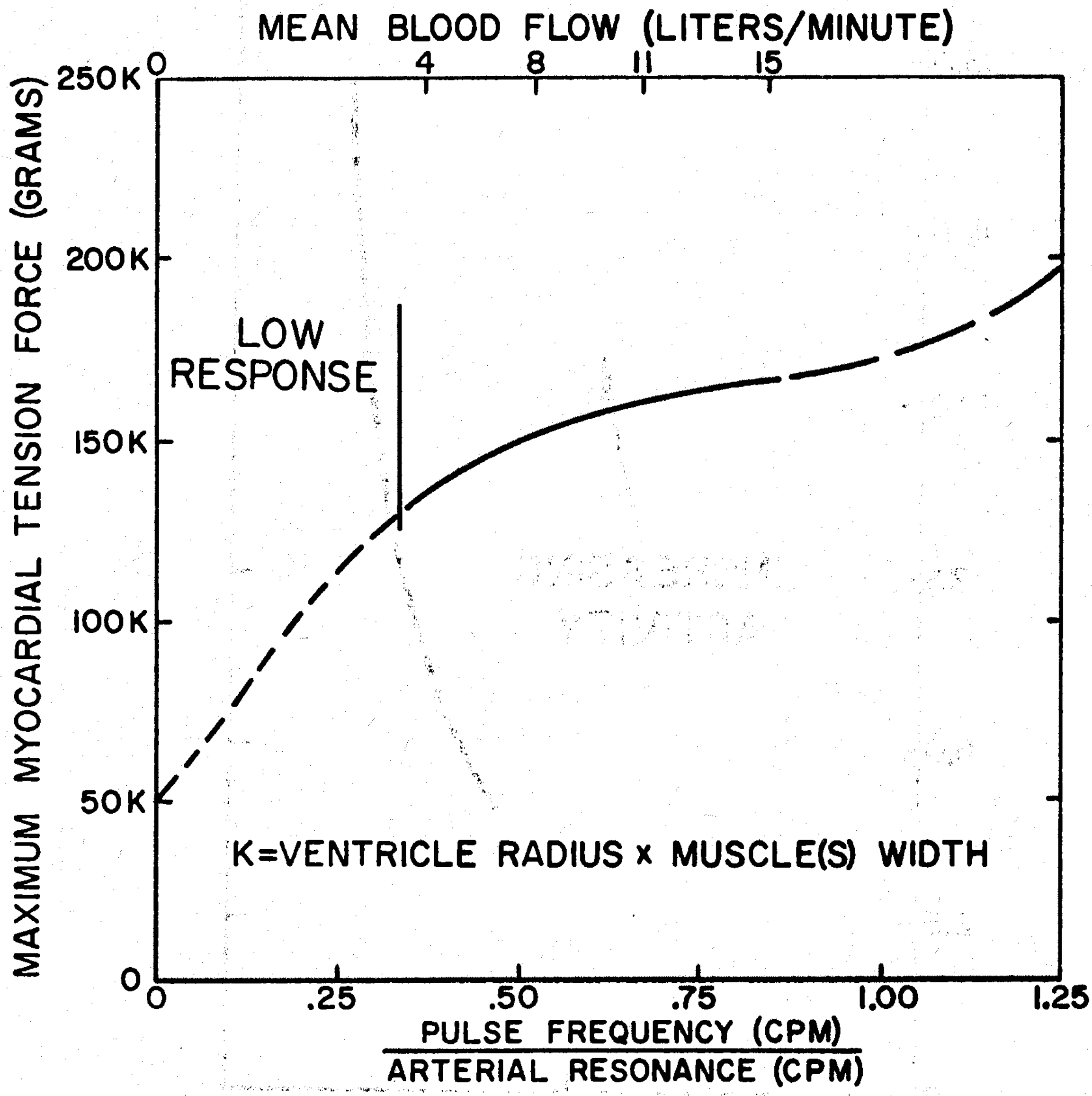

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Figure 6. Myocardial force characteristics (left heart).

Below pressures of 30 to 40 mm of mercury "the elasticity of the arterial tissue does not come into play to any notable extent" (ref 1, p 278). The arteries below these pressures behave like rigid tubes. (NOTE: At frequency ratios approaching zero, resonant systems behave rigidly.) The dotted line in figure 6 suggests the behavior of heart muscle force below the frequency ratio limit of 0.3. In this low-response region the slope of the curve becomes steeper for higher ratios, up to the point where the elastic properties become effective.

In the frequency regions where the vascular system is made to operate without limitation, the muscular force curve suggests kinship to highly damped force curves for resonant phenomena, by virtue of its flatness and later rising signature (presuming it does rise). Had the elastic properties of the circulation not reversed the rising character of the early curve, the myocardial forces required to achieve the range of flows encountered in the human would be much greater than 38 percent.

The nonlinear elastic properties of the circulation also probably play a role in shaping the muscle force curve of figure 6 (see ref 5, p 65).

Figure 7 relates energy expended by the heart to frequency ratio. This curve differs from the muscle tension curve in that it always continues to rise as pulse rate increases (fig. 4).

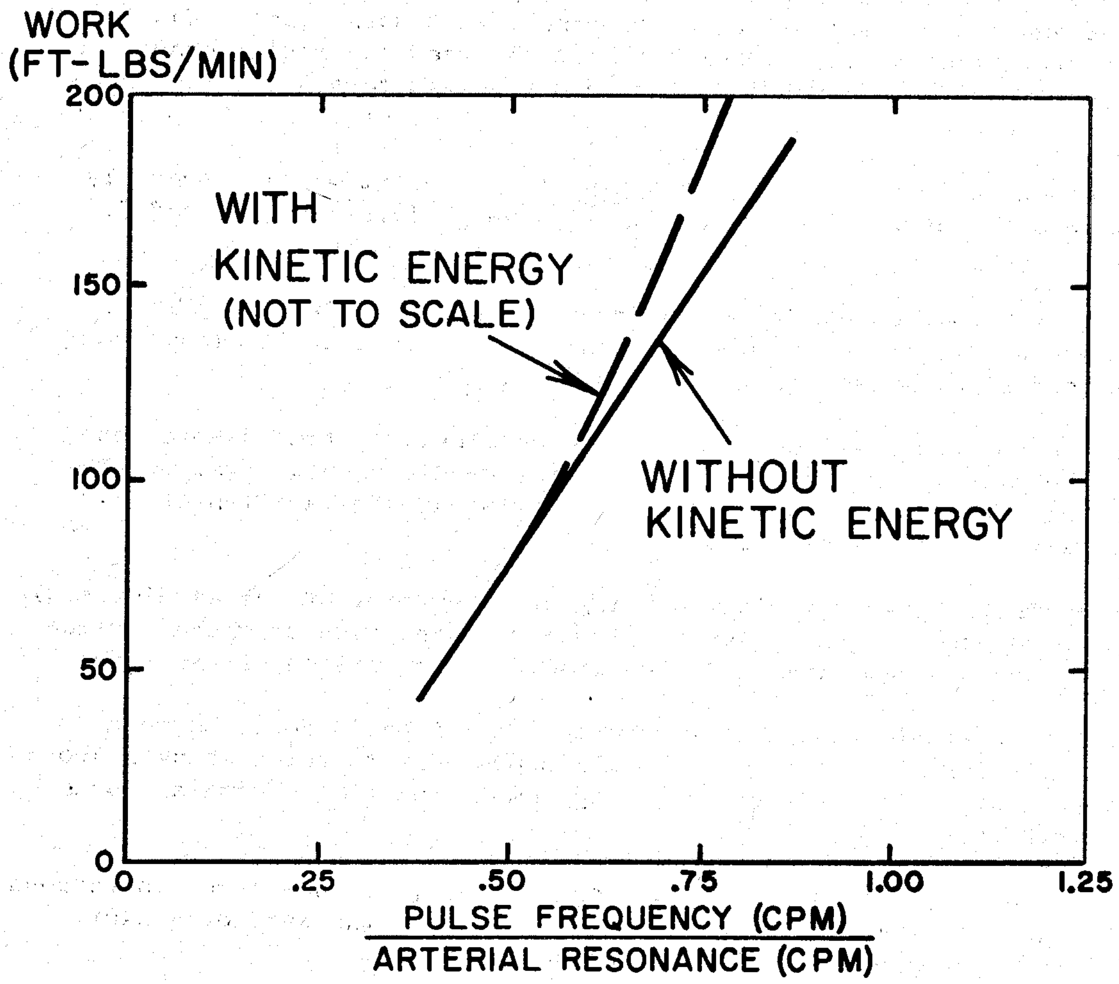
These few observations do not prove conclusively that damped resonant principles govern the operation of the cardiovascular system. The suggestion that it does is based on the following similarities of this system with simple resonant systems.

(1) The frequency ratios bounding the operation of the cardiovascular system correspond to the region in simple resonant systems where maximum exciting forces are minimal for a desired fixed excursion of the mass.

(2) For simple resonant systems the variation in force between these limits for minimal force is small compared with force changes above the upper limit. The cardiovascular system demonstrates a similar force characteristic.

(3) As the frequency ratio approaches zero, resonant systems respond less to the exciting forces. It would appear that the cardiovascular system at ratios approaching zero also acts stiffly.

An attempt was made to calculate the changes required in viscosity and some characteristic artery diameter for the range of blood pressures and flows observed in the human. Poiseuille's law was used. It was hoped that these calculations would show that the large range of flows could not be achieved solely by the evidenced pressure drops and the changes in viscosity and artery diameter. However the assumptions became so great that any realistic conclusion seemed remote.



108-62

Figure 7. Cardiac work.

If damped resonant principles do operate in the human cardiovascular system, one could suggest a few possible reasons for a pulsating heart and an elastic circulation system by comparing the performance of the human system as described herein with that of other engineering pump systems.

Reference 6 (p 1835) declares that positive-displacement reciprocating pumps in small and medium capacities are better adapted for high pressures than are centrifugal pumps. Or as a corollary, a reciprocating positive-displacement small or medium capacity pump can pump a given flow at higher pressures than centrifugal pumps of the same size. (NOTE: Centrifugal pumps have a nonpulsating output in contrast to the former type.) Hence, it might be suggested that flow requirements and compactness necessitated a positive-displacement type pump.

Conversely, pulsating pumps in contrast to steady-flow pumps produce large variations of stress in the associated rigid piping systems (ref 6, p 1835). By employing resonant principles in the arterial system's design, these stresses can be limited. It has been demonstrated that variation of peak stresses for up to a threefold increase in flow is only about 38 percent, and it is possible that up to a ninefold increase can occur without appreciably higher stress increases. If the vascular vessels acted rigidly with respect to the pulsating blood flows, a suggestion of the variation in stress might be had by examining the myocardial force curve (fig 6) for frequency ratios less than 0.3. The slope of the curve is much steeper in this region than in the region between 0.3 to 0.8, with steepness increasing with the higher ratios. It might be surmised therefore that if the phenomena of resonance did not operate above the 0.3 ratio, the myocardial forces (and energies) required to achieve the required flows would be much greater than they are. If these forces were not limited, the alternative is to use higher-strength vessel materials, which might penalize the designer in the areas of weight, energy expenditures, mobility, and porosity. An added advantage occurs by having tightly bounded forces operating in the system. The vessel materials are efficiently utilized. There is no need for excess materials. This characteristic is often used to reduce waste in engineering designs.

It is not feasible to continue a justification of the cardiovascular design on the basis of alternative approaches, but it may be that only a pulsing heart and an elastic circulatory system can satisfy all of the requirements imposed on the cardiovascular system.

An extension of these considerations with respect to the apparent resonant character of the system might lead to the development of a simplified empirical or mathematical model of the cardiovascular system assuming that the unknown elastic and related parameters can be determined. A model of this sort, if it did in fact describe the performance of the arterial system, would serve as a powerful tool, since now the contributions of individual changes in elastic properties of the circulatory system or in the rhythms of the heart could be evaluated for their effect on system performance; and appropriate measures, if available and applicable, could

be taken to correct the problem. Presently diagnostic procedures seem to depend heavily on the practitioner's experience in analysis.

10. RELATED MEDICAL RESEARCH

An integrated system approach to understanding the circulation's responsiveness to pulsed blood flows seems to be lacking in the medical literature, although numerous papers report on various aspects of system performance. The subsequent paragraphs present relevant dynamic properties of the vascular system as recorded in the literature.

It is suggested by Gregg (ref 1, p 278) that the flow of blood is pulsatile in the arteries, and because of their elastic properties and flow resistance, flow becomes continuous beyond the arterioles. This statement is probably based on the inability of present instrumentation to measure pulsed flows of very small magnitude. (Flow in the veins is generally nonpulsatile, and the vessel walls contain less elastic tissue than the arteries (ref 1, p 159) although they can distend appreciably under prolonged elevated intravenous pressures.)

There is one particularly important reason why the arterial system might require pulsed flows to the capillaries, and this regards critical closing pressures. Stacy (ref 4, p 373) suggests that smaller vessels require higher pressures than do larger vessels to hold them open for flow. At low pressures, it is possible that closure of the vessel might result "particularly if the tension exerted by the wall is increased appreciably by active contraction of the smooth muscle of the wall."

If, however, resonant principles operate in the arterial system as far as the arterioles and capillaries, figure 3 would suggest that very small pulsed forces acting in conjunction with the elastic properties of vessels could establish flow in tubes that under steady pressures of higher magnitude might be closed (or at least only partially open). This is especially true for lightly damped vessels. Hence, the small vessels, such as the capillaries, might sustain flows only because flows are pulsatile for pressures of the magnitude presented by the heart to the circulatory system.

Reference 1 (p 158) describes a very interesting fact concerning the periodic contraction of the metarterioles and the precapillary sphincters. "Briefly, blood flows generally from the arterioles directly into a metarteriole, and then into capillaries. The metarterioles lead directly into channels which are main thoroughfares from the capillary bed to the venules. The true capillaries concerned with interchange between blood and tissues are interanastomosing side branches of the main channels through the bed. At the ostia of each capillary is a small precapillary sphincter of smooth muscle, which is controlled by nerves presumably from the sympathetic nervous system, in the same manner that these nerves control the arterioles. In the body, the metarterioles and their precapillary sphincters undergo

periodic contractions at intervals of 15 secs to 3 min. When the tissue is in a resting state, the constrictor phase of this rhythm predominates and the precapillary sphincters may be completely closed. When the tissue becomes active, the dilator phase of the metarterioles predominate and the precapillary sphincters are open. Thus, in skeletal muscle, it is believed that the increase in blood flow with exercise comes in large measure from this opening up of large numbers of additional capillaries."

The fact that the sphincter acts as an elastic valve and that the sphincter and associated capillary branch off from the metarterioles may be significant. This elastic valve may require pulsed flows for adequate perfusion of the capillary. If it did not receive pulsed flows for its proper response, it could refuse to open sufficiently and the blood could be partially shunted through the metarteriole to the venule.

Incidentally, if resonant principles hold for the arterial system, extracorporeal pumps for long-term perfusion applications should be of the pulsatile variety with a pulse frequency adjustable to the patient's normal resting pulse. Adequacy of perfusion is in part judged by the maintenance of blood pressures and flows. Inadequate perfusion of the capillary beds could be masked by the higher pressures required for perfusion with steady flow pumps. This inadequacy might not manifest itself for short-time pump runs.

Peterson (ref 7) studied the reaction of the dog's cardiovascular system and elastic tubes of varying degrees of distensibility to artificially generated pulses of controlled character. He considered inertial, viscous friction and wall tension forces and their effect on modifying the artificial pulse introduced to the systems. It is concluded (1) that these vary in a nonlinear manner and each affects the other; (2) that the vascular pulse pressure is the sum of these forces; (3) that pulse pressure varies considerably in magnitude and in its component forces under various circulatory states even though 'stroke volume' remains constant.

When the artificial pulses were introduced into very distensible tubes, "the effective mass and viscous friction were so reduced that no induced pressure pulse was seen. The corollary is also true, that in rigid tubes these forces become very great." Nothing in the paper relates the frequency responsiveness of the circulations to the pulsed flows, and it would seem that herein lies the real message of this work.

The most comprehensive mathematical attempt found to describe the dynamic responsiveness of portions of the human cardiovascular system to the rhythmic pulsing of the human heart was in reference 8. Mollo-Christensen, a fluid dynamicist, considers mechanisms of energy transfer from fluctuations of the mean fluid stream, the viscous properties of the blood, the structures of the artery walls, the lateral and axially

symmetric oscillations of flexible tubes with the blood flowing through them for different degrees of fixity, etc. He makes the statement (ref 8, p 50) that "there is no doubt that the heart pumps the blood and that it generates a mean increase in pressure. Also, muscle contractions which compress the larger veins will propel the blood through the veins toward the heart."

But he suggests further "that the mechanical waves which are emitted by the heart and the larger arteries give up their energy in the small arteries, the arterioles and the capillaries, and that a fraction of this energy is used to propel the blood and overcome flow losses in the arterioles and capillaries."

The paper also suggests that the flow-smoothing role played by the larger arteries may be performed further away from the heart than originally thought to be the case "since the fluctuations do not decay very much in the brachial and femoral arteries." The paper emphasizes the complexity of the oscillations in the flow involving standing waves, reflected waves, self-excited waves, and traveling waves.

A process is suggested whereby axisymmetric waves can excite lateral waves further downstream as, for example, beyond a bend so that oscillating energy can be gradually transferred to shorter and shorter wavelengths of higher frequencies as the flow proceeds from the heart. Since the arterial system has complex modes of vibration and oscillation, it would be expected from the point of view of bounding energies and forces (fig. 3 and 4) that this would be the case for compatibility with the stiffer elastic properties of the smaller vessels. In other words, the same bounding frequency ratios may prevail as the pulsed flows, now of higher frequency, course through smaller vessels with higher natural frequencies. The ideas presented by Mollo-Christensen seem to be much more pertinent and basic to the problem of an accurate and comprehensive system description than previous attempts.

The last paragraph of this paper (ref 8, p 53) mentions "the possibility of a neuro-muscular coupling of the vibrations, which may be under central control as far as coupling gain is concerned." This may be the body's method for altering the circulation's responsiveness to pulsed flows under situations of stress, sickness, or disease to maintain bounded conditions.

11. CONCLUSION

It is suggested that the human arterial system may operate on principles that govern damped resonant systems generally. This conclusion is based on the close correlation observed between bounding pulse-arterial frequency ratios and the similarities existing between force and energy expenditures for the arterial system and for simple resonant systems. This suggests that any changes in the resonant character of the system or the pulsed flows generated by the heart, if sufficiently

great and uncorrected, can cause the heart to overwork and die prematurely or can cause the system to malfunction in other ways. It is further suggested without rigorous proof that only because resonant principles are employed, the heart and circulatory system may be able to meet the design requirements and restrictions imposed on them.

Within the bounds established for myocardial forces and energies by the resonant character of the system, it would also appear that the cardiovascular system is able to minimize flow losses by adjusting peripheral resistance and pulse rate.

12. ACKNOWLEDGEMENTS

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TR-1075, 7 February 1962, 22 pp text, 7 illus. OMS 501021.71201, DOFL Proj. No. 31000, UNCLASSIFIED Report.

A study was made from an engineering viewpoint primarily to determine the need for (1) a human heart that produces a pulsating rather than steady flow and (2) an elastic circulatory system. It is suggested that the normal rhythmic contractions of the heart may produce pulsed flows which resonate with the natural frequencies of the arterial system. As a consequence the magnitudes of the myocardial forces and energies expended by the heart would then be minimal and tightly bounded for large flow rate variations. Sufficiently great and uncorrected changes in either or both the resonant character of the arterial system or the pulsed flows may cause the heart to overwork and die prematurely or may result in other system malfunctions. Resonance then may possibly be a major physical design principle upon which the human cardiovascular system is based and which allows it to operate within its many constraints.

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